1 Introduction

Composite materials are extensively used in civil industry to produce relatively light-weight structures that are able to withstand large in-service loads [1]. A major challenge in the manufacturing of composite parts is to avoid that excessive residual stresses would appear. Such stresses can cause visible distortion of the structure and lead to premature failure. Residual strains may indeed initiate matrix cracking and delamination which results in a decreased strength of the complete composite structure. Many phenomena have been identified to be responsible for the creation of residual strains. The most important are: (i) chemical shrinkage of the matrix and (ii) mismatch between the thermal expansion coefficients of the constituent materials. These mechanisms induce the appearance of inter-laminar and intra-laminar residual strains. The manufacturing of a composite part with adequate quality thus requires to avoid the development of residual strains and distortions or at least to minimize their formation. However, only a few measurement techniques are available for in-situ monitoring of residual strain inside composite materials and most of these are not truly adequate. Therefore, there is a growing need for developing sensors which can straightforwardly monitor the development of internal strain during the cure process of composite materials.

Different techniques, including optical fiber sensor based methods, have already been proposed to monitor the strain in carbon fiber-reinforced polymer (CFRP) materials. Fiber Bragg grating (FBGs) based optical fiber sensors have for example proven their ability to measure the strain and the temperature within composite materials and hence they can be considered for measuring the build-up of residual strains during the cure cycle.

The main advantage of the use of FBG-based sensors comes from their small dimensions (the silica fiber diameter is generally around 125 µm) which enables them to be embedded inside composite materials with minimal distortion of the composite structure [2].

The majority of FBG-based sensors are fabricated in conventional step-index optical fibers. They have been used essentially to measure longitudinal strain (i.e. strain along the fiber axis) and temperature by monitoring the shift of the Bragg wavelength [3], [4]. However since those FBGs feature a significant cross-sensitivity between strain and temperature, the effect of temperature changes needs to be corrected for [5]. Furthermore during the composite material cure cycle, large temperature gradients arise and therefore knowing the temperature at the exact
location of the FBG sensor is rather complicated to achieve with classical thermocouples. To cope with this problem, one approach is to use an extra reference FBG that is embedded in the material without being exposed to strain and that only serves for recording the effect of temperature variations. The use of an FBG inserted in a capillary which isolates it from the strain field present in the material has been demonstrated in [6], [7]. Additionally, measurements based on recording the shift of the Bragg wavelength of FBG-based sensors written in conventional step-index fibers only allow quantifying the longitudinal strain whereas during the cure cycle of CFRP materials residual strain development is triggered by thermal strain induced in all three directions. The possibility to measure multi-axial strain in a host material with embedded FBGs has nevertheless been considered in several studies [8], [9]. These studies essentially relied on embedded FBGs written in highly birefringent fibers, for which the FBG reflection spectrum consists of two peaks, with each peak corresponding to one of the two orthogonally polarized modes propagating through the fiber. Therefore, in the case of these FBG-based sensors, the effective transverse strain applied to the fiber corresponds to the difference between the strain along the fast and slow axis of the fiber [10]. Yet in these sensors initial birefringence is present due to the difference between the thermal expansion coefficient of regular silica and that of doped silica used to create stress-applying regions in the fiber cladding. Therefore the sensor response is very sensitive to temperature variations and the use of temperature compensation systems remains mandatory.

Ideally one needs to be able to measure the residual strain arising during the composite material cure cycle in-situ, with sensors that can distinguish between the strains in the longitudinal and transverse directions and that can operate in a temperature independent manner. Developing such sensors is precisely our objective. In this work and to cope with the issues mentioned above, we report on the use of a particular type of highly birefringent microstructured optical fiber (MOF) to study the cure cycle of a CFRP material produced by a vacuum bagging autoclave technique. This MOF has been designed so as to feature a much larger sensitivity to transverse strain than conventional birefringent fibers [11], [12]. Furthermore, the MOF features a very low sensitivity of its phase modal birefringence to temperature [13]. In Section 2 of this article, we present the design of our MOF and the specific characteristics of an FBG written in its core. In Section 3, we demonstrate the possibility to integrate this particular MOF inside a carbon/epoxy material and we calibrate the sensor response to axial and to transverse loads. Section 4 reports on the use of such MOF in combination with FBGs in regular single mode fibers to monitor the manufacturing process of a composite structure in order to obtain insight on the cure cycle that would be difficult to detect with any other sensor technology. To close this manuscript we conclude on the potential of this MOF based sensor in the field of cure cycle monitoring.

2 Fiber Bragg grating in highly birefringent microstructured optical fiber

A microstructured optical fiber (MOF) is an optical fiber that has a regular pattern of air holes running parallel to the fiber axis and along its entire length [14]. This type of optical fiber can be optimized for a large range of applications by tailoring the number, the size and the positions of the air holes that form the light confining microstructure around the fiber core [15], [16]. Illuminating the fiber core with an interference pattern of UV light induces a permanent refractive index change in the core of the fiber with a period equal to that of the interference pattern. The resulting FBG acts as a wavelength selective micro-mirror that reflects light at a wavelength that is proportional to twice the period of the index variations [17]. The main advantage of FBGs for sensing applications is that these devices perform a direct transformation of the sensed parameter to

![Fig. 1. SEM image of the cross-section of the MOF under study.](image-url)
optical wavelength, independent of the optical power level, of connector or fiber losses, or of other FBGs at different wavelengths. The fabrication of FBGs in the core of such fibers has been reported several times [18], [19], [20], [21]. It relies on the photosensitivity of the glass with which the core region of the fiber is fabricated. The cross-section of the MOF employed in this work is shown in Fig. 1. The core of this MOF has a GeO$_2$-doped inclusion that allows for the inscription of FBGs with conventional ultraviolet inscription techniques. Because of the birefringence of the fiber an FBG written in the fiber core will reflect two Bragg wavelengths $\lambda_{B1}$ and $\lambda_{B2}$, one for each orthogonally polarized mode. The spectral distance between these two peaks is called the ‘peak separation’ $\Delta\lambda$ and is given by $\Delta\lambda = 2 \cdot B \cdot \Lambda$ with $B$ the phase modal birefringence and $\Lambda$ the grating period. This MOF has been designed such that its phase modal birefringence exhibits a high sensitivity to transverse strain (ten times larger than that reported for conventional highly birefringent fiber [11]) whilst being (almost) insensitive to temperature changes [13], [22].

This low thermal response stems from the origin of the modal birefringence which is mainly due to waveguide birefringence. The high hydrostatic pressure and transverse strain sensitivities of the proposed MOF are linked to the mechanical asymmetry of the microstructured region, which generates a large difference in the normal stress components in the fiber core. As illustrated in Fig. 2 with results of finite-element simulations performed with the commercially available software Comsol Multiphysics® [23], the specific air-hole microstructure allows transferring externally applied stress to the core region along one of the fiber symmetry axes. This enhances the sensitivity of the fiber to pressure and to transverse load. The waveguide properties of this MOF are fully detailed in [13]. Moreover, we demonstrated in [11] that the sensitivity of an FBG inscribed in the core region depends on the direction of the load with respect to the angular orientation of the microstructure. The sensor response is the largest when the load is applied along the slow axis of the fiber (cf. Fig. 1). This corresponds to the orientation for which the directions of the fundamental optical axes are aligned with the directions of the principal stresses. In the next sections and in order to sense the out-of-plane strain in composite materials, the MOFs are embedded with the fast axis aligned with the plane of the composite layer.

Fig. 3 shows an example of a reflection spectrum of an FBG inscribed in the core of the proposed MOF. This reflection spectrum has been measured with a commercially available FBG-interrogator that has a wavelength measurement resolution of 1 pm from FBGS International [24]. The initial peak separation of the grating inscribed in the proposed MOF is about 1.45 nm at $\lambda = 1557$ nm which leads to an initial modal birefringence of about $1.37 \times 10^{-3}$. By measuring the changes of the peak separation one can perform temperature insensitive transverse strain measurements.
3 Calibration of the embedded FBGs in carbon/epoxy materials to axial and transverse loads

The highly birefringent MOFs described in the previous section have been embedded at mid-thickness of a symmetric laminate lay-up ([90,0]$^2$s) with a total thickness of 2.56 mm (prepreg material M10T300 provided by Hexcel [25]) and their response has been monitored for axial and transverse loads. A schematic of the carbon/epoxy coupon is presented in Fig. 4. The composite laminates have been processed in an autoclave using the vacuum bagging technique [1]. The optical fibers are placed in between the two middle 0° layers, in the same direction as the carbon fibers to reduce the eventual distortion and non-uniformity of the composite structure in the neighboring of the optical fiber.

3.1 Calibration of the embedded FBGs to axial loading

First, the carbon/epoxy coupons have been subjected to axial load (along direction 1 in Fig. 1) to investigate the response of the embedded FBGs. The specimens have been tensile tested on an INSTRON 8801 machine at a cross-head displacement speed of 0.1 mm/min up to a maximum tensile strain of 1500 µε. An extensometer placed onto the sample at the exact location of the embedded FBGs has recorded the elongation of the composite material at the sensors’ position. The sensor response to axial strain (cf. Fig. 5) is linear and its sensitivity has been calculated to be -0.031 pm/µε. Since the peak separation is sensitive to the difference of strain in the fiber core along the slow and fast axes (which are aligned with the out-of-plane and in-plane directions respectively), the shift of peak separation is due to the contraction in the out-of-plane direction of the cross-ply laminate (as given by Poisson’s ratio).

3.2 Calibration of the FBGs through the thickness direction

We evaluated the response of the embedded FBGs to transverse load (along direction 3 in Fig. 4) by compressing the coupons between two metal blocks on an INSTRON 5800R machine at a cross-head displacement speed of 0.02 mm/min. The transverse strain applied to the composite coupon is estimated from the load applied to the sample, the contact surface between the sample and the metal blocks and the material parameters of the CFRP [25], [26]. The samples have been loaded up to a maximum value of
approximately 5.5 kN. The sensitivity of the peak separation to transverse strain is linear and reaches a value of -0.17 pm/µε as shown in Fig. 6.

Finally, the calibration performed on the embedded FBGs shows that any changes in the peak separation would essentially be due to transverse effects. Therefore, the transverse strain acting on the fiber can be quantified from the value of the sensor sensitivity to transverse strain previously calculated and from the change in peak separation of the MOF.

In the next section, we investigate the possibility to exploit these specific characteristics to monitor the cure cycle of carbon/epoxy material.

4 Cure cycle monitoring of carbon/epoxy material with FBG-based sensors

4.1 Experimental set-up

A network of FBG-based sensors has been embedded inside of a carbon/epoxy plate of 230 x 640 mm² (M10T300 from Hexcel [25]) and the response of the sensors has been monitored during the complete cure cycle. Fig. 7 shows the schematic of the composite specimen with the positions of the different sensors. The composite part is made of three main zones with different thicknesses: (i) the ‘current zone’ has a quasi-isotropic lay-up of 20 plies [0/45/0/-45/0/45/0/-45/0/90]s, (ii) the ‘thick zone’ is composed of 36 plies with lay-up [0/45/0/-45/0/45/0/-45/0/90/0/45/0/-45/0/45/0/-45]s and (iii) the ‘drop-off zones’ which are built with a 2.5 mm single layer step from the 11th ply to the 26th ply. This type of structure is representative for design singularities currently found in the field of aeronautics.

The location of the FBGs has been chosen such that the development of the residual strain is monitored at different locations of the composite sample (regions with different lay-up and thickness). The MOF has been embedded at mid-thickness of the ‘current zone’ in Fig.. The angular orientation of the embedded MOF is the same as in the previous section, i.e. with the slow axis (cf. Fig. 1) aligned with the out-of-plane direction of the laminate sample. Three FBGs written in a regular optical fiber at different wavelengths have been embedded along the 1-direction of the sample; the FBGs have been placed respectively in the current zone, in the drop-off and in the thick zone. These FBGs have been encapsulated within silica capillaries in order to shield them from transverse strain and so that they are only exposed to temperature effects and to longitudinal strain. The composite specimen has also been instrumented with several thermocouples which are either embedded in the composite structure or surface mounted at several locations close to the FBGs. More information on the composite sample lay-up and on supplementary instrumentation with flexible ultrasonic transducers can be found in [27]. In the current study, we rely on the MOFs to assess the transverse strain components and on the FBGs protected from the transverse effects to identify the longitudinal strain built-up during the cure cycle.

The composite coupon has been manufactured with the vacuum bagging technique in an autoclave. The responses of the different sensors and of the thermocouples have been recorded during the entire cure cycle.

4.2 Results of the composite cure cycle monitored with FBG-based optical sensors

The entire manufacturing process has been monitored by following the Bragg wavelength changes of the regular FBGs in capillaries and the peak separation changes of the gratings in our MOF. Fig presents the changes in the peak separation during the cure cycle together with the temperature variation recorded by a thermocouple placed in close vicinity with the MOF sensor (TC6 as presented in Fig. 7. Schematic of the optical fiber network embedded in the composite specimen. The coordinate system of the laminate is indicated.
Fig. 8. Changes in the temperature and in the peak separation $\Delta \lambda$ during the entire cure cycle. The temperature profile is recorded with thermocouple TC6. [The numbered grey circles drawn on the temperature profile correspond to the cycle times at which the spectra shown in Fig. 9 have been recorded].

Fig. 7). Fig. 8 evidences a first drop of the peak separation (part B) which can be correlated with the polymerization of the sample. The cooling phase (part D) features a large decrease of the peak separation associated to the build-up of residual strains during the consolidation phase. This graph shows that we can distinguish between two stages in the cure cycle: a first stage up to approximately 100 minutes, during which the resin becomes fluid and the composite material is not yet formed; and a second stage, after 100 minutes until the end of the cycle, during which one can consider that the composite material has been created.

The reflection spectra of the MOF gratings have been recorded at several times during the cure cycle, as indicated in Fig. 8, in order to verify that the spectra were not deformed during the cycle. Fig. 9 shows these spectra: we do not detect any deformation which means that the strain state around the MOF is homogenous and that the measurements performed with the FBGs are reliable.

Since the phase modal birefringence of the MOF is inherently insensitive to temperature as explained in Section 2, the changes in peak separation are due to thermally induced transverse strain coming from the modification of the strain state in the composite sample during the cure cycle. Even though the load during the calibration (Section 3.2) differs from that created by the cure cycle, an estimation of the transverse residual strain developed in the CFRP structure during the manufacturing can be assessed. This needs to be done with caution though, since in the calibration test of Section 3.2, the MOF was compressed along direction 3 while during the cure cycle, the MOF is compressed in all directions. The peak separation of the MOF grating depends on the difference between the transverse in-plane strain (direction 1 in the schematic presented in Fig.) and the transverse out-of-plane strain (through the thickness). In the composite structure under test, the MOF is embedded in a quasi-isotropic lay-up and therefore we expect that the in-plane strain will be low in comparison with those through the thickness. Furthermore, the MOF has been embedded in the composite structure with a particular orientation such that the fiber slow axis (which is the most sensitive axis of the fiber) is aligned with the direction of the out-of-plane strain. Moreover the fast axis, which is about five times less sensitive [11], is aligned with the in-plane strain direction. We can therefore make the assumption that the strain arising through the thickness is mainly responsible for any changes in the peak separation of the MOF grating. Hence and according to the sensor calibration performed in Section 3.2, the strain through the thickness can be linked to the changes in the peak separation measured by the MOF sensor. In region B indicated in Fig, the drop of the peak separation is about 22 pm which corresponds to a
compressive transverse strain of ~ -130 με. In region C, the sensor signal is almost constant meaning that no transverse strain is measured by the MOF sensor. One can therefore reasonably assume that the cure reaction has been completed and that the composite material is formed. The cooling down to room temperature (part D) is associated with a large decrease of the MOF signal and thus with the development of substantial transverse residual strains in the composite material. The large decrease of the peak separation (275 pm) results in a transverse strain of ~ -1620 με.

In order to check the transverse strain values previously calculated from the MOF signal, we estimated the coefficient of thermal expansion in the direction through the thickness of the composite specimen. Taking into account the temperature variation during the last cure cycle step (part D), we obtained a value of the coefficient of thermal expansion to be 3.0×10^{-5}/°C which is very close to the indexed coefficient of thermal expansion for this material equal to 2.5×10^{-5}/°C. The values given here are only a first approximation. The confidence interval for the calculated values is not yet assessed. We also calculated the axial strain from the encapsulated FBGs embedded in the 1-direction of the composite plate. The wavelength shifts of these gratings have been corrected for temperature variations according to the method described in [28]. From that measurement and according to our calculations, the axial strain is about 130 με which is less than 10 times lower than the residual strain developed in the transverse (in part D). This confirms our initial assumption that the transverse residual strains in such a thick composite structure are dominant.

5 Conclusion

In this paper, we have shown that it is possible to efficiently integrate fiber Bragg grating based sensors in CFRP to monitor their manufacturing process. For this purpose, we used a highly birefringent microstructured optical fiber specifically designed to feature an enhanced sensitivity to transverse strain. From the calibration of the embedded sensors to axial and transverse loads, we could show that their response mainly depends on the transverse strain applied on the sensors. Finally we have shown that this microstructured fiber based sensor can be used to monitor the entire cure cycle of a CFRP structure. The sensor allows assessing the onset of polymerization and quantifying the internal residual strain in the composite material that was created as a result of the fabrication process.

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